Deformation Compensation of Ram Components of Super-heavy-duty CNC Floor Type Boring and Milling Machine

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Abstract

Ram is a very important component of super-heavy-duty computer numerical control (CNC) floor type boring-milling machine, and deformation of ram is a significant source causing errors in machining process. To compensate the deformation error of super-heavy-duty CNC floor type boring-milling machine, based on force analysis theory, the law and compensation measures of deformation of ram are researched. Based on the principle of torque (force) balance of the ram components, the formulas of compensation forces and compensation torques are derived, the relations between compensation forces (compensation torques) and the stroke distance of the ram are given. According to theoretical analysis results and the structural characteristics of super-heavy-duty CNC floor type boring and milling machine of TK6932, rods compensation, hydrostatic pressure compensation and wire rope compensation measures are taken to compensate the deformation error of ram. The experiments and computer simulation results show that the straightness of the ram at its overhanging end meets the national machinery industry standards.

Keywords: boring and milling machine; deformation; error compensation; computer simulation; ram

1. Introduction

Floor type boring and milling machine is a general machine tool for large part machining, which has been widely applied in fields such as aviation, aerospace, energy, metallurgy, transportation and ship. The boring spindle and milling spindle are installed inside of ram, so deformation of the ram components is the main influence factor of spindle accuracy.

With regard to the issue of the ram deformation compensation, some significative researches and findings have been obtained. ASQUITH Company of British designed a hydrostatic device, in which the thin films feedback was used to compensate bowing of ram [1], but the device is difficult to make due to its complicated structures. RAPID-5 milling and boring machine of German WOTAN Company applied electro-hydraulic proportional control method to compensate bowing of the ram [2], but this method will produce a large deviation of compensation when ram moves rapidly. BSF milling and boring machine of Toshiba series adopted hydraulic gravity center compensation method, in which a balanced hammer was installed at front end of spindle box to balance bowing of ram caused by gravity center change of spindle box [3-4]. References [5]-[7] proposed numerical control (NC) system compensation method, where an endpoint compensation was realized by a NC-code transformation and in the case of a compensated path generation, the effect of translational and rotational errors on the position of a tool reference point can be fully compensated [8]. However, there are some problems of this method in practice. In the common case, a tool is not spherical but cylindrical or flat, the physical orientation...
of the tool will still affect the machining result[9]. Besides, there are some other compensation methods such as hydrostatic bearing and hydraulic cylinder compensation methods [10-13], rod compensation method [14-18], modification shape method under the prestressing force [19], and so on. For the super-heavy-duty floor type boring and milling machine researched in the paper, the section size of ram is 680 mm×780 mm, the maximum stroke distance of ram is 2 000 mm, so it is hard to meet the accuracy requirements of machine by only one simple compensation method.

In this paper, deformation compensation of super-heavy-duty CNC floor type boring and milling machine of TK6932 is studied, the formulas of compensation forces and compensation torques are derived. In addition, the relations between compensation forces (torques) and stroke distance of ram are also given. Considering the structure characteristics of super-heavy-duty CNC floor type boring and milling machine, the compensation measures for the ram’s deformation are given, and the correctness and feasibility of the studied methods are verified through experiments and computer simulation.

2. Working Principle and Deformation Influence Factors of Ram

2.1. Working principle of floor type boring and milling machine

Column, ram, spindle, spindle box, slide carriage and lathe bed are major components of super-heavy-duty CNC floor type boring and milling machine, as shown in Fig. 1. The column is fixed on the slide carriage and moves with the slide carriage along the lathe bed. The spindle box moves up and down along the column, the ram installed on the spindle box moves back and forth along it, and the cutter mounted on the front face of the ram rotates with the spindle which is fixed in the ram.

2.2. Influence factors analysis

The deformation of the ram components (not including the column) of super-heavy-duty floor type boring and milling machine is shown in Fig. 2, where the dotted lines indicate the situation after deformation. The deformation of the ram components consists of four aspects: 1) deflection caused by the weight of ram and its accessories; 2) bowing of the ram caused by gravity center changing of the ram; 3) bowing of the spindle box caused by gravity center changing of the ram; 4) deformation of the column.

![Fig. 2 Deformation of ram components.](image)

Firstly, when the ram extends out, the weight of the ram and its accessories will cause the deflection of the ram; secondly, the bowing will appear with the additional torque caused by gravity center change of the ram; thirdly, the equilibrium state of the spindle box is also damaged under the additional torque, and this will lead to bowing of the spindle box; finally, the whole weight of the ram components is supported by the column, and the gravity of the ram components will cause deformation of the column, and which in turn causes tilting of the ram.

Usually the deformation of the column can be ignored, because it has little effect on the precision of spindle rotation. So the compensations should include bowing of the spindle box, bowing of the ram, deflection of the ram and deflection of the boring spindle. The deflection of the boring spindle can be compensated through CNC system by changing the value of feed rate in the same direction of deflection. In this paper, the remaining three aspects of deformation are considered, that is, bowing of the spindle box, bowing of the ram and deflection of the ram.

3. Theoretical Analysis of Deformation Compensation

3.1. Bowing compensation of spindle box

Spindle box moves on the column, and its weight is mainly borne by ball screws and static guides installed on the column. As the spindle box is too heavy, ball screws and static guides cannot bear such huge gravity loads independently, so a balanced hammer must be installed to balance the gravity of spindle box.

When the ram is in its initial position, the ram components are in a equilibrium state. Force diagram of the spindle box is shown in Fig. 3.
Force balance equations of the spindle box are as follows:

\[
\begin{align*}
N_1 + N_2 &= G_0 + G \\
T_0 s + G_0 a + Gb &= N_2 c
\end{align*}
\]  

where \(N_1\) is the supporting force on spindle box exerted by feeding ball screw, \(N_2\) the pull force on the spindle box exerted by balanced hammer, \(G_0\) the gravity of the spindle box, \(G\) the gravity of the ram, \(T_0\) the initial compensation force (\(T_0\) and \(T_0'\) are equal in size and opposite in direction, which form a couple to balance the additional torque produced by the moving of ram), \(s\) the horizontal distance between the couple, \(a\) the distance between gravity center of the spindle box and the center of ball screw, \(b\) the distance between gravity center of ram and the center of ball screw, and \(c\) the distance between the exerted force point of balanced hammer and the center of ball screw.

When the ram moves for a stroke distance of \(l\), its gravity center may locate on the left side or the right side of ball screw, so the additional torques produced by the moving of the ram can be expressed in two situations.

**Situation 1:** gravity center of the ram locates on the right side of ball screw.

Force diagram of the spindle box on Situation 1 is shown in Fig. 4(a), and the force balance equations can be written as follows:

\[
\begin{align*}
N_1 + N_2 &= G_0 + G \\
T_0 s + G_0 a + G(b - l) &= N_2 c
\end{align*}
\]  

where \(T\) is the compensation force when the ram moves for a stroke distance of \(l\).

Connecting Eq. (1) with Eq. (2) can obtain

\[
(T - T_0) s = Gl
\]  

**Situation 2:** gravity center of the ram locates on the left side of ball screw

Force diagram of the spindle box in Situation 2 is shown in Fig. 4(b). Similarly, the balance force equation is written as:

\[
(T - T_0) s = G(l - b)
\]  

Eq. (3) and Eq. (4) can be obtained:

\[
\Delta T = \frac{Gl}{s}
\]  

where \(\Delta T\) is the increment of compensation force, \(\Delta T = T - T_0\).

Equation (5) shows that, the increment of compensation force is only related to the stroke distance \(l\) of ram, and it has nothing to do with the position of ram gravity center, and the force to compensate bowing of the spindle box can be calculated through the above equations.

### 3.2. Bowing compensation of ram

The ram contacts the spindle box through hydrostatic film. The film pressure fluctuates with gravity center changing of the ram, which will cause change of the film thickness. So, a relative displacement in the vertical direction will generate between the ram and the spindle box, that is, bowing of the ram will occur. In addition, the gap between the ram and the spindle box will increase this bowing. Similar to the bowing of the spindle box, the main reason of the ram bowing is the overturning torque caused by gravity center change of the ram.

When the ram is in the initial position, forces diagram of the ram is shown in Fig. 5(a), in which the ram can be regarded as a backwards cantilever. In Fig. 5(a), \(A\) and \(B\) are supporting points of hydrostatic guides, and \(a\) and \(b\) are the distance between gravity center of the ram and the two supporting points respectively. Its gravity center locates between the two supporting points, so force balance equations of the ram can be expressed as

\[
\begin{align*}
(N_{al} - N_{a2}) + (N_{bl} - N_{b2}) &= G \\
(N_{al} - N_{a2}) a - (N_{bl} - N_{b2}) b &= 0
\end{align*}
\]
where $N_{A1}$ and $N_{A2}$ are hydrostatic pressures at supporting point $A$, and $N_{B1}$ and $N_{B2}$ are hydrostatic pressures at supporting point $B$.

According to Eq. (6),

$$
\begin{cases}
N_{A1} - N_{A2} = \frac{Gb}{a+b} \\
N_{B1} - N_{B2} = \frac{Ga}{a+b}
\end{cases}
$$

(7)

Gravity center of the ram changes with the stroke distance of the ram, and then overturning torque will generate. As the ram moves for a stroke distance of $l$, the gravity center of the ram will move for a corresponding distance of $l$. Forces diagram of the ram is shown in Fig. 5(b).

According to Eq. (6),

$$
\begin{cases}
\Delta N_A = (N'_{A1} - N'_{A2}) - (N_{A1} - N_{A2}) = \frac{Gl}{a+b} \\
\Delta N_B = (N'_{B1} - N'_{B2}) - (N_{B1} - N_{B2}) = \frac{Gl}{a+b}
\end{cases}
$$

(10)

Equation (10) shows that the increment of pressure at supporting point $A$ is $Gl/(a+b)$, and the increment of pressure at supporting point $B$ is $-Gl/(a+b)$. The increment of pressure at two supporting points is equal in size and opposite in direction, which forms a pair of couple. In order to keep balance, a compensation torque $M$ must be exerted on the ram, and the value of $M$ is given as

$$
M = \frac{Gl}{a+b}(a+b) = Gl
$$

(11)

Equation (11) shows that bowing compensation torque of the ram is in direct proportion to the ram’s stroke distance $l$, and the compensation torque $M$ can be accurately calculated through Eq. (11).

3.3. Deflection compensation of ram

The deflection of the ram is a kind of bending deformation caused by the weight of the ram, milling and boring axes, and other accessories. The ram has an irregular shell structure with cuboid shape. For the convenience of analysis, the structure of the ram can be regarded as a simple continuous beam with equal square cross-section, and the gravity load of the ram can be transformed into uniform load. Thus, the ram is turned to a continuous beam bearing uniform loads.

Rods compensation method is a general method of deflection compensation of the ram. We can exert an external load on the beam to generate a bending deformation which is opposite in direction and equal in size with deflection of the ram.

A Forces diagram of the ram under rods compensation is shown in Fig. 6. In which, $F_1$ and $F_2$ are the pull force of the rods (producing the eccentric compression effect), $q$ is the uniform load exerted on the ram, $e$ the distance between the point of force and $Z$ axis of the ram in cross-section of the ram, $\theta$ the angle between neutral plane (horizontal plane) and plane determined by centerlines of pull rods and centerline of the ram.

$$
\Delta N_A = (N'_{A1} - N'_{A2}) - (N_{A1} - N_{A2}) = \frac{Gl}{a+b} \\
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$$
\Delta N_A = (N'_{A1} - N'_{A2}) - (N_{A1} - N_{A2}) = \frac{Gl}{a+b} \\
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$$

(10)

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than the maximum stroke distance of the ram, so the forces of the second group bearings cannot be considered. A force diagram of the ram is shown in Fig. 7.

![Force diagram of the ram](image)

When the stroke distance of the ram is $l$, in order to keep the deflection of the ram equal to zero, the deflection produced by the two rods must be equal to the deflection of the ram caused by its gravity.

$$\frac{Ml^2}{2EI} = \frac{F_0l^3}{3EI} + \frac{ql^4}{8EI}$$  \hspace{1cm} (12)

where $M$ is compensation torque produced by the two pull rods, $F_0$ force exerted by the first group bearings, $E$ material elastic modulus of the ram, and $I$ moment of inertia of the ram's section.

Compensation force of two pull rods is equal in size, Suppose $F_1=F_2=F$, according to Fig. 6, torque $M$ produced by compensation force $F$ can be expressed as

$$M = 2eF\sin\theta$$  \hspace{1cm} (13)

According to Eq. (12) and Eq. (13), the compensation force $F$ can be written as:

$$F = \frac{M}{2e\sin\theta} = \frac{8F_0l + 3ql^2}{24e\sin\theta}$$  \hspace{1cm} (14)

Equation (14) shows that, the size of compensation force depends on $l$, $e$, $F_0$, $q$ and $\theta$. For the given machine tools, $F_0$, $q$, $\theta$ and $e$ are determinate, so the size of compensating force $F$ is only the function of $l$. That is to say, with fixed value of $l$, compensation force $F$ can be accurately calculated through Eq. (14).

4. Measures of Deformation Compensation

4.1. Measures of bowing compensation of spindle box

The theoretical analysis shows that, in order to compensate bowing of the spindle box, it is necessary to balance the overturning torque caused by gravity center changing of the ram. The measure of bowing compensation of the spindle box is shown in Fig. 8.

![Measure of bowing compensation of spindle box](image)

The compensation principle is as follows:

With the ram moving out from the spindle box, the gravity center of the ram will change, and the overturning torque will generate, so the ram will tilt gradually, and the tension force of the wire rope will increase also. At the same time, the data of the electronic dynamometer will be changed, and then, the numerical control system will send signals to servo motor to shorten the wire rope, which will generate a couple to compensate the bowing of the spindle box. The size of the couple can be calculated through equations given in Section 3.2.

4.2. Measures of bowing compensation of ram

Considering the characteristics of hydrostatic guide, the hydrostatic method is applied to compensating bowing of the ram. The advantage of the method is that compensation torque is generated by the hydraulic pressures of hydrostatic guides with no additional compensation devices. Measures of bowing compensation of the ram are shown in Fig. 9.

![Measures of bowing compensation of the ram](image)

The compensation principle is as follows:

1) The four hydrostatic pressure chambers are divided into two groups. The hydrostatic guides located in upper top of the spindle box and the ones located in rear bottom of the spindle box are the first group; the hydrostatic guides located in upper bottom of the spindle box and the ones located in rear top of the spindle box are the second group.

2) As the ram moves forward, it will tilt in the direction of anteroinferior. We can increase the pressure value of the first group with $Gl/(a+b)$, and decrease the pressure value of the second group with $Gl/(a+b)$, thus,
a counterweight torque of $G_l$ will compensate bowing of the ram.

4.3. Measures of deflection compensation of ram

The compensation measures are shown in Fig. 10. Considering the structures of the ram and its characteristics of free expansion, two thin rods are installed in the ram near the top wall, and the deflection compensation is implemented through the pull forces served by two hydro-rods.

![Fig. 10 Sketch map of hydro-rods compensation.](image)

The compensation principle is as follows:

With the ram moving out from the spindle box, the gravity center of the ram will change, so the ram will generate a bending deformation under the force of its weight. According to the theoretical analysis results in Section 3.3, the bending deformation of ram can be eliminated by a reverse bending. The reverse deformation is generated by the two hydraulic cylinders pulling the two thin rods, as shown in Fig. 10. The pull force of two rods can be accurately calculated through Eq. (14).

5. Verification of Compensation Effect

According to the expression of compensation forces and compensation torque, finite element analysis (FEA) technique is applied to verifying the effect of deformation compensation of the ram components. The simulation analysis results of TK6932 are illustrated in Fig. 11.

![Fig. 11 FEA simulation results of compensation.](image)

Figure 11 shows that, after implementing compensation measures, the deformation of the ram at the hanging top end is less than 0.02 mm, while the ram is located at its maximum stroke distance of 2 000 mm.

In order to verify the correctness of theoretical analysis and finite element simulation, adjusting experiments of machine tool have been done, and the data of deformation of the ram field measuring is shown in Table 1. In experiments, the spindle box is located 2 000 mm away from the base of machine tool in vertical direction.

<table>
<thead>
<tr>
<th>Stroke distance of ram/mm</th>
<th>Deformation of ram / ($10^{-2}$ mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without compensation</td>
</tr>
<tr>
<td>500</td>
<td>+2</td>
</tr>
<tr>
<td>1 000</td>
<td>+14</td>
</tr>
<tr>
<td>1 500</td>
<td>+28</td>
</tr>
<tr>
<td>2 000</td>
<td>+44</td>
</tr>
</tbody>
</table>

Note: “−” indicates that the deformation of the ram is upward, “+” indicates that the deformation of the ram is downward.

Table 1 shows that, with compensation measures executed, the deformation of the ram at the end of overhanging is less than 0.02 mm, which meets the precision standard of floor type boring and milling machine tools ruled by the national machinery industry [20] ($\leq 0.02 \text{ mm}/500 \text{ mm}$).

6. Conclusions

1) Based on the principle of torque (force) balance, deformation compensations of the ram components of super-heavy-duty CNC floor type boring and milling machine are analyzed, the formulas of compensation forces and compensation torques are derived respectively, and these formulas provide a helpful condition for accurate calculating and controlling of compensation forces (compensation torques).

2) According to results of theoretical analysis and the structure characteristics of TK6932, the measures of deformation compensation of the ram components are presented, and these measures provide a foundation for ensuring principal axis precision.

3) The results of simulation and experiments show theoretical analysis and measures of deformation compensation given in the paper are reasonable and feasible, the straightness of the ram at its overhanging end meets the national machinery industry standards. These measures not only increase the adjusting efficiency of machine tool, but also provide a new way to solve similar problems of machine tools.

References


Biography:

WU Fenghe received Ph.D. degree from Beihang University in 2006. Now he is a professor in Department of Mechanical Engineering, Yanshan University. His main research interests include digital design and measurement, performance analysis and structure optimization of machine tools.

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